EFFECTS OF OVERLOADS ON FATIGUE CRACK GROWTH AND CRACK CLOSURE IN METASTABLE AUSTENITE

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Experimental investigations are reported concerning the influence of mechanically induced phase transformation on overload induced retardation of fatigue crack growth in FeNiC alloys. Crack propagation and crack closure are followed using a sophisticated differential dynamic compliance technique. As compared to stable austenitic material a moderately enhanced retardation but a shortened delay are observed. It is suggested that in the highly metastable austenite, both the altered residual stress state ahead of the crack tip and the enlarged residual deformations left in the wake of the advancing crack might be counterbalanced by the extra strain, which props the crack tip open.

INTRODUCTION

It is well known that mechanically induced martensitic transformation in metastable austenitic steels, which is accompanied by volume expansion and shear processes, provides an extraordinary combination of tensile properties, i.e. significantly enhanced hardening capacity and tensile ductility. This "transformation plasticity" led to the development of the class of TRIP-steels and enables the toughness and strength level of metallic as well as ceramic materials to be enhanced simultaneously, an effect being termed "transformation toughening".

Under fatigue loading a beneficial effect is suggested to occur as long as the transformation zone is non-vanishing in size but yet confined to the crack tip region. The resulting mean load shift within the cyclically loaded crack tip zone due to the built-up of residual compressive stresses promotes an increased crack propagation resistance. It is suggested that crack closure is intensified too. But the experimental findings are not conclusive. The influence of phase transformations on fatigue crack growth has been investigated almost exclusively under constant amplitude loading.(1-5). The objective of the present research is to evaluate the load interaction effects following tensile overloads. Apart from specific aspects of transformation plasticity this should shed some light on basic questions of the micromechanics of fatigue crack propagation concerning the role excerted by crack closure and residual stresses.

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EXPERIMENTAL PROCEDURE

Materials. The basic mechanical properties at room temperature of the materials used in this study are listed in Table 1. The metastable austenitic model alloy Fe-23%Ni-0.3%C alloy was thermomechanically treated to achieve different austenite grain sizes with different austenite stability, i.e. microstructures with a mean grain size of about 50µm (MA50) and 140µm (MA140), resp. (10). For comparison purposes a stable austenitic alloy, Fe-30%Ni-0.3%C, as well as the commercial stainless steel X6CrNiTi18.10 (denoted with SA50, (9)) were included into the experimental program. The data in Table 1 clearly demonstrate the superior hardening capacity of the metastable alloy as compared to the stable austenite and, furthermore, the extremely low austenite stability of the coarse grained microstructure (MA140) with sacrifice of the ductility.

TABLE 1: Tensile Properties of the investigated materials at room temperature: Fe-23%Ni-0.3%C (10) and X6 CrNi Ti 18 10 (9)

Micro-structure	0.2% Yield Stress σ_y, MPa	transformation stress σ_t* MPa	transformation strain ε_t** %	σ_t x $(1+\varepsilon_t)$	UTS MPa	UTS/σ_y	Elonga-tion %
MA 50	210.5	521.7	19.5	623.4	779	3.70	106.6
MA140	186.1	210.8	1.0	212.9	807	4.34	33.6
SA50	336.0	--	--	--	623	1.85	61.5

* : stress for the begin of deformation induced martensitic transformation
** : strain for the begin of deformation induced martensitic transformation

Specimens and Methods. The fatigue crack propagation experiments were performed with single-edge notched specimens having a width of 20mm and thickness of 10mm. A 4mm long starter notch with a root radius of 0.12mm was introduced by spark machining, which ensured crack initiation at sufficiently low stresses. The tests were conducted at 5080 Hz (sine wave) in laboratory air. In the overload tests the crack was grown at least ten times the fatigue plastic zone size past the previous overload before another overload was applied. The experimental program covered a range of base-line stress intensity levels (ΔK= 8 to 15MPa$\sqrt{m}$), load ratio (R=0.1 and 0.5), and overload ratios (K_{OL}/K_{max}=1.25; 1.5, 1.75; 2.0).

The tests were conducted using a DYNACOMP resonance fatigue machine operating in load control (7). A personal computer was used for data acquisition, function generation, and process control. The crack length was continuously monitored through measuring the resonance frequency which enabled almost continuous load shedding to maintain constant base-line ΔK conditions. Intermittent overload cycles were run quasistatically per manual control. Crack closure was evaluated in preselected intervals of the test by means of a dynamic compliance technique through measuring the alteration of the period of minor resonance vibrations in dependence on the stress level within a fatigue cycle (8).

RESULTS AND DISCUSSION

Constant Amplitude Cycling. The near-threshold crack propagation behavior of the metastable microstructures is illustrated in Fig. 1a. The threshold values derived from these curves are summarized in Fig. 1b in dependence on the load ratio R for both microstructures. The data for R0.8 were determined by means of load shedding with K_{max}=const. Obviously, the coarser grained microstructure exhibits a much higher crack growth resistance not only at low but also at high load ratios. This effect which contrasts to the reduced ductility is suggested to be due to the higher propensity of the coarse grained microstructure to mechanically induced phase transformation, thus resulting in intensified residual compressive stresses ahead of the crack tip.

TABLE 2: Fatigue Crack Growth Properties of the investigated materials at room temperature under constant amplitude cycling at R=0.10

Material	ΔK_{th} $MPa \cdot m^{1/2}$	$\Delta K_{th,eff}$ $MPa \cdot m^{1/2}$	C	m
MA 50	4.0	2.4	2.93×10^{-11}	2.545
MA140	9.0	3.0	3.38×10^{-14}	4.350
SA 50	6.0	2.4		

The effective threshold values derived from crack closure measurements are included in Fig.1b. They are about the same for both metastable microstructures, but only slightly larger than the threshold values of the respective martensite after deep-cooling (10), which were nearly independent on the austenite grain size. It is concluded, therefore, that the influence of microstructure and load ratio can not be accounted for solely by crack closure arguments. In accordance with fractographic and closure observations it is believed that the difference in the threshold values between the fine grained and coarse grained metastable materials resulted primarily from the residual compressive stresses built up through the martensitic transformation and, thus, is a direct consequence of the metastability of the austenite.

Overload effect. The fatigue crack growth behavior is known to be strongly affected by the loading sequence. A single tensile overload results in a transient behavior of the fatigue crack growth rate. As the crack grows into the overload zone, it gradually slows down until the minimal growth rate is achieved and then slowly recovers the steady-state crack growth rate. The transient fatigue crack growth behavior following a single tensile overload is illustrated in Fig. 2a and 2b. As an example, the overload effect in the metastable austenitic microstructure MA50 is shown for the baseline stress intensity range $\Delta K = 12 MPa \cdot m^{1/2}$ and load ratio R=0.1 as a function of the overload ratio $K_{OL}/K_{B,max}$. It can be seen that the metastable austenitic microstructure exhibits the common overload retardation The overload effect is intensified with increasing overload ratio, with the crack becoming arrested even at $K_{OL}/K_{B,max}$ =2 in this case. Remarkably crack arrest occurred almost immediately after the overload in metastable austenite, which contrasted to the usual behavior of cracks becoming arrested only after some additional crack advance as observed in SA50.

An enhanced retardation effect was observed for the highly metastable austenite (MA140), whereas the retardation effect in the MA50 was only slightly higher but of the same order of magnitude as for both the stable austenitic alloy Fe-30Ni-0.3C and the X6CrNiTi18.10(SA50) steel. For the highly metastable MA140 an anomaleous behavior is observed in that a very strong retardation occured at an overload ratio even as small as 1.25 with crack arrest for 1.5. But crack growth reinitiated following a subsequent overload of 1.75 and 2.0, resp. This probably occured because the transformation zone was no longer confined at this stage.

The crack closure behavior is exemplified in Fig. 3a and 3b. In both cases crack arrest was observed after the overload application and reinitiation occurred after 10% load increase. The compliance technique clearly revealed crack tip blunting during overload application and the development of a second "near-tip" closure effect thereafter. Differences are found regarding the closure distance (a_{eff}-range) as well as the closure load (K_{op}) with both measures being reduced in the metastable material. Interestingly, after application of the overload the effective crack length at K_{min} remained unchanged in the stable SA50 which is in marked contrast to its increase in MA50, thus indicating additional crack opening in the latter case.

CONCLUSIONS

1. A single tensile overload results in a similar retardation phenomenon in both stable and unstable austenite, but with the crack growth rate being almost suddenly reduced in the metastable material, whereas in the stable austenite the growth rate slows down more gradually after overload application
2. Transformation induced excess deformation during overload application enforced enhanced retardation in highly metastable alloys though significant crack tip blunting and subsequent diminuition of "far field" closure occured.
3. It is suggested that the beneficial overload effect in MA140 is caused by the enlarged residual streses ahead of the crack tip combined with the development of a near-tip closure phenomenon.
4. Concerning crack closure the influence of stress state on yielding and plastic deformation seems to be counterbalanced by the influence of the stress state on the near-tip phase transformation and the resulting residual stress level.

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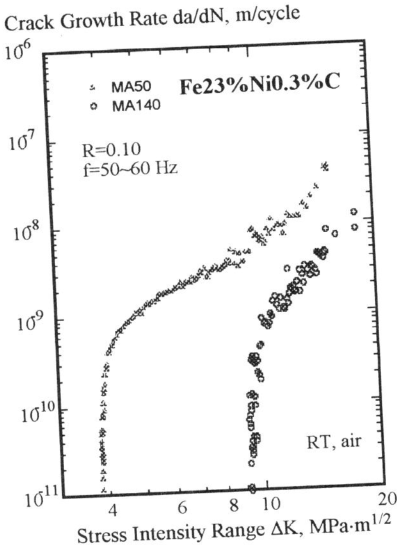

Fig. 1a: Near-threshold fatigue crack propagation behavior in the metastable austinitic alloy Fe23%Ni0.3%C at R=0.1.

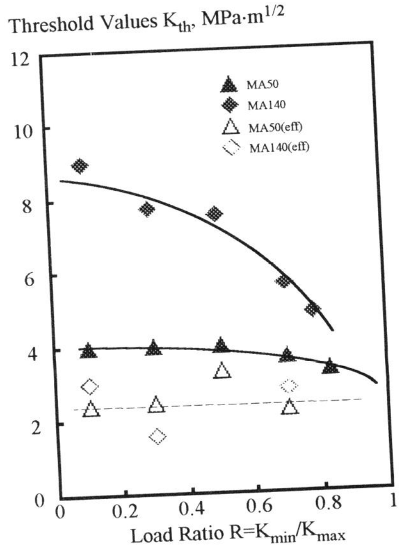

Fig. 1b: Fatigue crack propagation threshold values of the metastable austenitic alloy Fe23%Ni0.3%C dependend on grain size and load ratio.

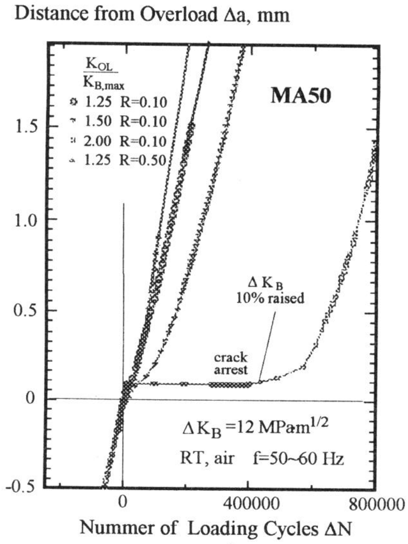

Fig. 2a: Fatigue crack growth behavior as influended by overloads

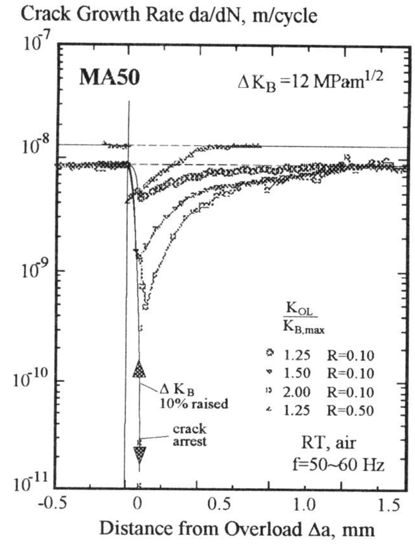

Fig. 2b: Crack growth rate as influenced by intermittent overloads

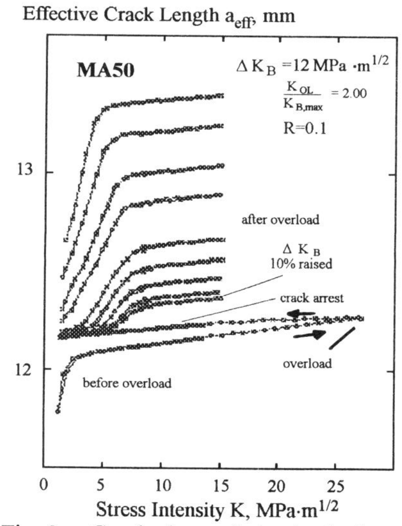

Fig. 3a: Crack closure behavior in the course of an overload test in the finer grained metastable alloy.

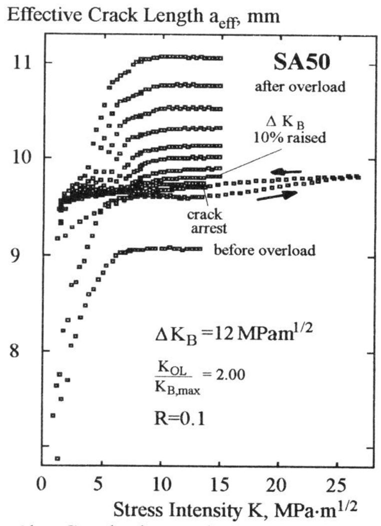

Fig. 3b: Crack closure behavior in the course of an overload test in the stable austenitic steel.